Principles of beam intensity

Physics | Modern Physics | Production & use of X-rays

Difficulty level	Group size	Preparation time	Execution time
hard	2	45+ minutes	45+ minutes

This content can also be found online at:

http://localhost:1337/c/5fa1ae18d6b04000035a710b

General information

Application

Setup

Most applications of X rays are based on their ability to pass through matter. Since this ability is dependent on the density of the matter, imaging of the interior of objects and even peaple becomes possible. This has wide usage in fields such as medicine or security.

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Other information (1/2)

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Prior knowledge

The prior knowledge for this experiment is found in the Theory section.

Main principle

Laboratory based X-ray sources are in most cases polychromatic, meaning that the spectrum of the source consists of an energy range instead of a single distinctive energy peak. This has a lot of influence on the X-ray measurements that are performed. Especially the relation of the pixel count on the digital detector versus the beam power is important for optimal image quality.

Other information (2/2)

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Learning objective

The goal of this experiment is to get to know the principles behind beam intensity.

Tasks

1. Determine the variation in beam intensity.
2. Investigate the inverse square law.

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Theory (1/14)

Detector saturation

With digital X-ray imaging, X-ray photons that interact with the detector are converted to a digital signal. Such a digital detector is composed of a raster of pixels (picture elements) and each pixel can be considered as bucket. For each interaction of an X-ray photon with the detector, a series of electrons are produced in the pixel corresponding with the location of the photon interaction. These electrons are stored in the pixel, gradually filling up the bucket. After a set time interval, "exposure time", the electron content of the pixel is measured by emptying it. For the same intensity of X-ray's, a longer exposure time will results in a larger number of pixels in the bucket.

Each digital detector has a limited bucket size which is called the 'full well capacity' of the detector. When this level off fill is reached, additional electrons are thrown away because the detector is saturated. A saturated detector will cause inconsistent measurements and has thus to be avoided.

Theory (2/14)

Detector calibration

Each digital detector has a different and variable offset and pixel-specific output. During the calibration these variations will be measured and used in the subsequent imaging.
Even without the X-rays on, the detector will generate a read-out value that is different from 0, called 'dark image'. This has several reasons from which the main reasons are an electronic offset and read-out noise. When determining the beam intensity $\mathrm{I_0}$, it is important to subtract this offset ($\mathrm{I_D}$) from the measured read-out ($\mathrm{I_{0,M}}$).

$$\mathrm{I_0 = I_{0,M} - I_D}$$

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Theory (3/14)

Another issue that exists, is that the sensitivity of every detector pixel is slightly different, resulting in a wide variation of I0 values for every pixel. During calibration, these variations are recorded. After calibration, the Transmission value for every pixel (I) is recalculated based on the beam intensity of that pixel at that time (I_M), the beam intensity during calibration ($I_{0,M}$) and the dark current intensity (I_D) during calibration.

$$T = \frac{I_M - I_D}{I_{0,M} - I_D}$$

If the calibration was successfully performed, after calibration the images have grey-values between 0 and 1.

Theory (4/14)

Generation of X-rays and polychromaticity

In an X-ray source, electrons are accelerated over a certain voltage before hitting the target material where X-rays are formed. The electrons are generated through thermionic emission from a heated fila-ment at the cathode side. The emitted electrons are accelerated towards the target, at the anode side, by a high voltage applied between the cathode and the anode. The amplitude of the acceleration voltage corresponds to the kV settings (between 0 and 35 kV) applied on the source and the current value corre-sponds to the amount of electrons that reach the target.

When the electrons, that all have the same acceleration (keV), bombard the target a series of events oc-cur when the electrons lose their energy due to impact. In most cases (99%), the kinetic energy of the electrons will be converted to heat but in some cases they also generate characteristic and Bremsstrah-lung X-ray photons. These photons are used for the imaging process.

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Theory (5/14)

The Bremsstralung or braking radiation is generated when an electron is decelerated. During decelera-tion, the kinetic energy that the electron loses is transferred to an X-ray photon. The electron can lose a part of its energy or all of its energy. Because of this variation, the resulting photons will have a variety of energies, but all smaller than the maximal kinetic energy of the incident electron (keV). The spectrum of the X-ray photons leaving the source will thus be relatively broad with a maximum corresponding to the acceleration voltage, for this reason the spectrum is called polychromatic in adverse to monochromatic, where all the photons have a single energy.

In addition to the continuous bremsstralung spectrum, the interaction of an incident electron with the atoms of the target material can cause the generation of characteristic X-ray photon, which have a certain energy.

The spectrum that comes out of an X-ray source is a combination of the bremsstralung and the characteristic X-ray photons.

Theory (6/14)

Source power in function of kV and current

The intensity of the X-ray photon beam is determined by various parameters but in general we can say that the beam intensity is proportional to the target power (P). The target power corresponds to the total energy of the electron beam hitting the target, i.e. the combination of acceleration voltage (U) and current (I).

$$\mathrm{I} \propto \mathrm{P_{target}(Watt)}$$

$$\mathrm{P_{target}(Watt) = U(kV) + I(mA)}$$

The target power for source settings of 20 kV and 0.3 mA is the same as for 30 kV and 0.2 mA.

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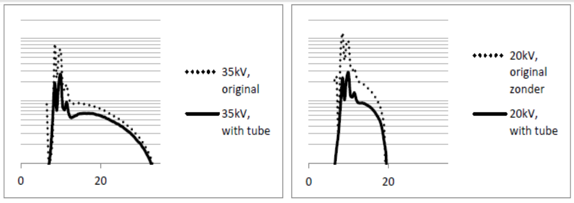
Theory (7/14)

In reality, the detected beam intensity is not identical for both settings due to several reasons. one of the main causes is the polychromatcity of the beam. As the X-ray source consists of a vacuum chamber with glass tube, the tube itself will cause important filtration, mainly for the lower energy X-ray photons. As the average photon energy of the 20 kV spectrum is lower than the 30 kV spectrum, a larger part of the pho-tons will be stopped by the tube, and thus have a lower intensity. This also causes the beam to have a higher average energy than before it was filtered, this is called hardening the beam.

Additionally, the energy dependant sensitivity of the detector and other effects will add up to that effect.

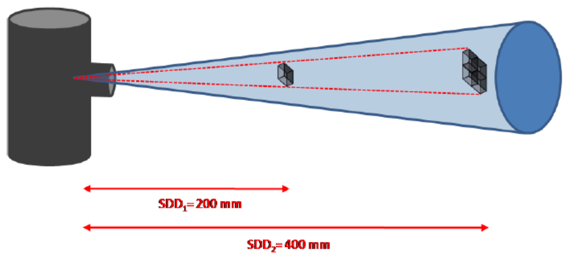


Beam intensity, inverse square law

Theory (8/14)

The intensity of the beam is defined by the amount and energy of the X-ray photons hitting each pixel. If a pixel, that is positioned at a certain position (ex $\mathrm{SDD_1} = 200\ \mathrm{mm}$)measures and intensity $\mathrm{I_1}$, the intensity $\mathrm{I_2}$ in the same pixel will be four times lower if its distance to the source is doubled (ex. $\mathrm{SDD_2} = 400\ \mathrm{mm}$). The reason for this is that the beam intensity is proportional to the surface it is projected on. The size of the beam that hits the pixel at the first position has the ability to illuminate four pixels of the same size at the second position. This is called the 'inverse square law' as the decrease in intensity is the square of the increase in distance from the source.

$$\mathrm{I_2} = \frac{\mathrm{SDD_1^2}}{\mathrm{SDD_2^2}} \cdot \mathrm{I_1}$$



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Theory (9/14)

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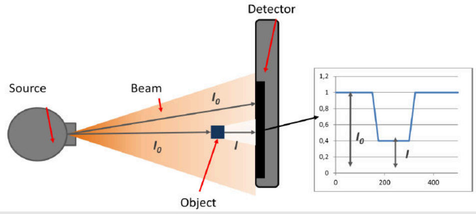
Transmission and Attenuation

In X-ray imaging, the transmission or attenuation of X-rays through a certain object are measured. Depending on the settings of the source, a beam with a certain intensity $\mathrm{I_0}$ is measured by the detector when no object is placed between the source and the detector. When an object is placed in the path of the beam, this object will attenuate the beam so that the detector measures a smaller intensity I instead of $\mathrm{I_0}$.. The remaining intensity I compared to the original $\mathrm{I_0}$ is called transmission (T), which is the opposite of the attenuation (A)of the object. For a calibrated detector, the beam intensity is rescaled to a value between 1 and 0. With T = 1 for the beam without an object in front of the detector ($\mathrm{I_0}$).

$$\mathrm{T_{obj}} = \frac{\mathrm{I}}{\mathrm{I_0}} = 1 - \mathrm{A_{obj}}$$

$$\mathrm{A_{obj}} = \frac{\mathrm{I_0 - I}}{\mathrm{I_0}} = 1 - \mathrm{T_{obj}}$$



Theory (10/14)

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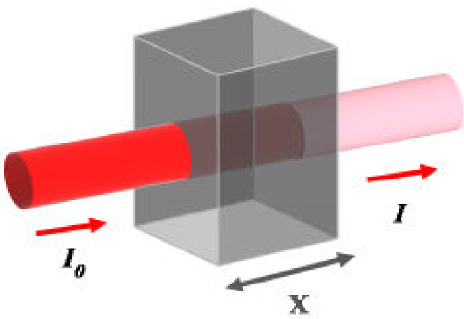
Influence of kV and material

The transmission of a certain object ($\mathrm{T_{obj}}$) is determined by its chemical composition, its density and its thickness as described by the Lambert-Beer law:

$$\mathrm{T_{obj}} = \frac{\mathrm{I}}{\mathrm{I_0}} = e^{-\mu \mathrm{x}}$$

with μ the linear attenuation (1/cm) coefficient and x the thickness (cm). The linear attenuation coefficient is different for every material but also varies in function of the X-ray photon energy. For the same materi-al but varying material thickness and two different photon energies E1 and E2, the transmission will decrease with increasing thickness and will increase for a higher energy. For example if E1 is higher than E2 it could look like this:



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Theory (11/14)

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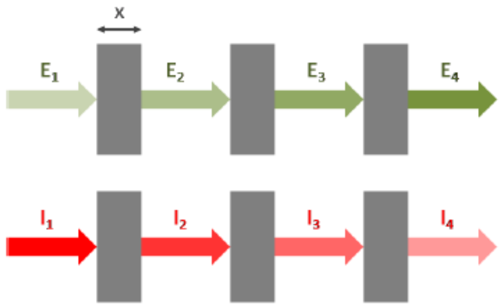
Beam hardening and filtration

A polychromatic X-ray beam consists of X-ray photons with different energies. As the lower-energy pho-tons are absorbed more rapidly, the beam becomes harder (higher mean energy) as it passes through an object.

If the beam was monochromatic, the mean energy of the beam would not change will passing through several slabs of the same material and same thickness, only the intensify would. The transmission (T) for each of the three slabs separately would be identical.



Theory (12/14)

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E1 = E2 = E3 = E4

$$\mathrm{I}_1 > \mathrm{I}_2 > \mathrm{I}_3 > \mathrm{I}_4$$

$$\mathrm{T}_1 = \frac{\mathrm{I}_2}{\mathrm{I}_1} = \mathrm{T}_2 = \frac{\mathrm{I}_3}{\mathrm{I}_2} = \mathrm{T}_3 = \frac{\mathrm{I}_4}{\mathrm{I}_3} = e^{-\mu \mathrm{x}}$$

As the linear attenuation coefficient (μ) is energy dependant, but the mean energy remains the same, the total transmission ($\mathrm{T}_{\mathrm{tot}}$) through the three slabs equals the product of the three transmission:

$$\mathrm{T}_{\mathrm{tot}} = \frac{\mathrm{I}_4}{\mathrm{I}_1} = \mathrm{T}_1 \cdot \mathrm{T}_2 \cdot \mathrm{T}_3 = e^{-\mu(3\mathrm{x})}$$

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Theory (13/14)

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When the beam is polychromatic, the mean energy of the beam will increase as it passes through the different slabs:

E1 < E2 < E3 < E4

$I_1 > I_2 > I_3 > I_4$

$T_1 = \frac{I_2}{I_1} = e^{-\mu_1 x}$

$T_2 = \frac{I_3}{I_2} = e^{-\mu_2 x}$

$T_3 = \frac{I_4}{I_3} = e^{-\mu_3 x}$

As the linear attenuation coefficient (μ) is energy dependant and mostly decreasing with increasing photon energy. The transmission for each of the separate slabs will decrease.

$\mu_1 > \mu_2 > \mu_3$

$T_1 < T_2 < T_3$

The total transmission (T_{tot}) through the three slabs equals the product of the three transmission:

$T_{tot} = \frac{I_4}{I_1} = T_1 \cdot T_2 \cdot T_3 = e^{-(\mu_1 x + \mu_2 x + \mu_3 x)}$

Theory (14/14)

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If μ_A is considered as the average linear attenuation coefficient over the three slabs, calculating the thickness of one slab with μ_A would result in an overestimation of the thickness while for more than three slabs it would result in an underestimation of the thickness.

$T_{tot} = e^{-(\mu_1 x + \mu_2 x + \mu_3 x)} = e^{-3\mu_A x}$

If $T_1 = \frac{I_2}{I_1} = e^{-\mu_A x}$ then $x_1 > x_2$ because $\mu_A < \mu_1$

The beam hardening will not increase in a linear way but rather gradually decrease when the thickness is augmented. In order to diminish the beam hardening effect in an imaging process it is therefore advised to use some filtration. The filtration will cause the beam to harden prior to interacting with the sample. If, the filtration is adopted before the calibration of the detector, the measured transmission will be more correct for various thicknesses.

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Equipment

Position	Material	Item No.	Quantity
1	XR 4.0 expert unit, 35 kV	09057-99	1
2	XR4 X-ray Plug-in Cu tube	09057-51	1
3	XR 4.0 X-ray Computed Tomography upgrade set	09185-88	1

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Setup and Procedure

Setup

Attach the XRIS to its stage.
Place the Digital X-ray detector XRIS on the rail at position 25 cm. The back side of the XRIS stage corresponds to its position on the rail. This position is called the 'source to detector distance' SDD (mm).

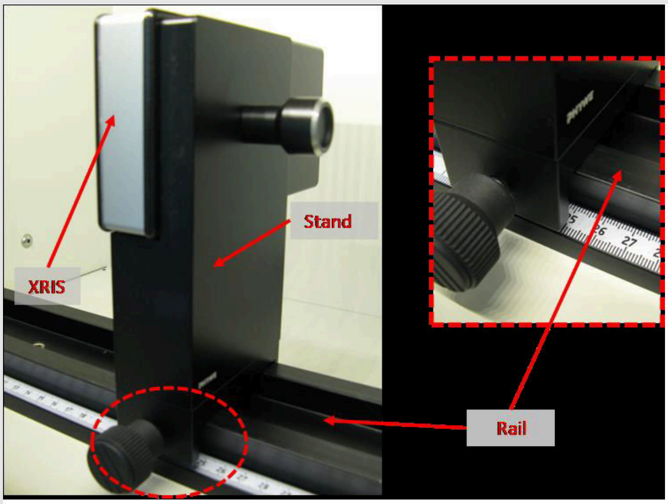

Fig. 1: Set-up of the XRIS

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Procedure (1/2)

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- Connect the X-ray unit via USB cable to the USB port of your computer (the correct port of the X-ray unit is marked in Fig. 2).
- Connect the usb cable of the detector to the computer
- Start the “measureCT” program. A virtual X-ray unit , rotation stage and Detector will be dis-played on the screen. The green indication LED on the left of each components indicates that its presence has been detected (Fig. 3)
- You can change the High Voltage and current of the X-ray tube in the corresponding input windows or manually on the unit. (Fig. 3)
- When clicking on the unit pictogram additional information concerning the unit can be re-trieved(Fig. 3).

Fig. 2: Connection of the computer

Procedure (2/2)

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- The status pictogram indicate the status of the unit and can also be used to control the unit such as switching on and off the light or the X-rays (Fig. 3).
- The position of the digital detector can be ad-justed to its real position either by moving the XRIS pictogram or by filling in the correct value in the input window. (Fig. 3).
- The settings of the XRIS can be adjusted using the input windows. The exposure time controls the time between two frames are retrieved from the detector, the number of frames defines how many frames are averaged and with the binning mode the charge of neighbouring pixels is aver-aged to reduce the total amount of pixels in one frame.

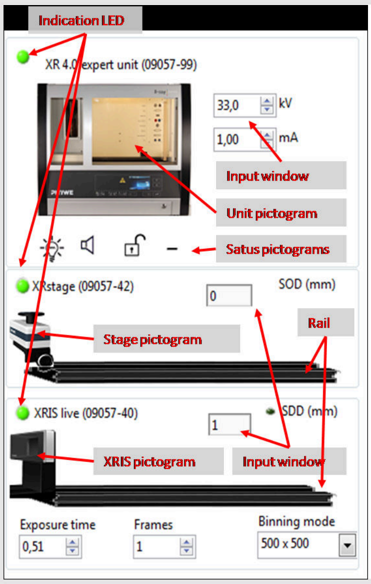

Fig. 3: Part of the user interface of the software

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Experiment execution

Determine the variation in beam intensity

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- Adjust the XRIS settings and X-ray unit settings according to Fig. 4 or load the configuration from the predefined CTO file 'Experiment 3' (see Fig. 5).
- Start a new experiment, give it a unique name and fill in your details (Fig. 5). Alternatively it is also possible to load this experiment with pre-recorded images and open this manual. The correct con-figuration will be loaded automatically as well but the functionalities of the software will be limited to avoid overwriting the existing data.

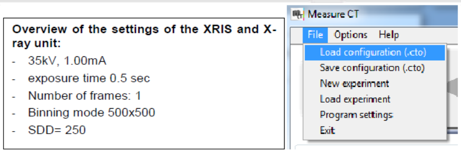

Fig. 4: The settings for this experiment (left panel)and the method load and adjust the settings (right panel)

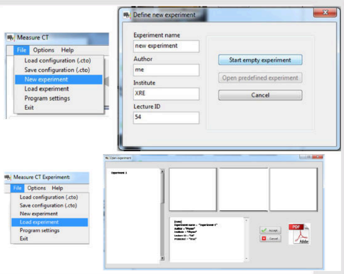

Fig. 5: How to create a new or open an existing experiment

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Determine the variation in beam intensity (part 2)

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- Check whether the detector is not saturated for the highest power (35 kV, 1 mA) (see experiment 1).
- Switch of the X-ray source and wait a couple of seconds. Activate the 'live view'. Wait long enough between the image to allow the source and detector to adjust to the new settings (3 - 5 sec). Deacti-vate the 'live view'.
- Take on image with the X-rays of and save it as DI_500ms in the tiff format.
- Switch on the X-rays.

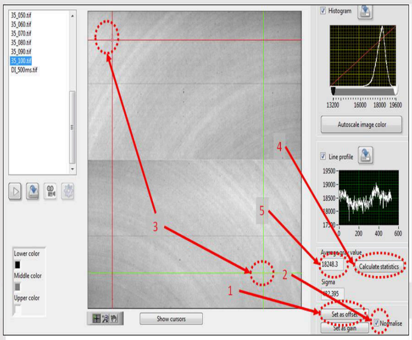

Fig. 6: How to normalise for dark current and calculate the pixel count

Determine the variation in beam intensity (part 3)

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- Take un-calibrated images at 35 kV but change the current in steps of 0.1 from 0 to 1 mA, save the images accordingly. Wait long enough between the image to allow the source and detector to adjust to the new settings.
- Take un-calibrated images for 20kV but change the current in steps of 0.1 from 0 to 1 mA, save the images accordingly.
- Open the viewer.
- Double click on the DI_500ms image, 'Set as offset image' (see Fig. 6.1) and normalise (see Fig. 6.2). This way the detector dark current is subtracted from the images.
- Double click on one of the other images. Select a large, central region of image 'see Fig. 6.3), calcula-te the average pixel count (average grey value), (see Fig. 6.4 and 6.5) in that region and write it down.
- Repeat this for all the images that were saved.

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Determine the variation in beam intensity (part 4)

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- Put the results in a table and calculate the power for every setting (see Fig. 7).
- Make a plot of the resulting pixel counts in function of the current (see Fig. 8).
- Make a plot of the resulting pixel counts in function of the power (see Fig.9).

35 kV		
current(mA)	power (W)	Intensity(counts)
1	35.0	18250
0.9	31.5	16404
0.8	28.0	14530
0.7	24.5	12613
0.6	21.0	10697
0.5	17.5	8756
0.4	14.0	6827
0.3	10.5	4930
0.2	7.0	3100
0.1	3.5	1430
0	0.0	0

20 kV		
current(mA)	power (W)	Intensity(counts)
1	20	2531
0.9	18	2254
0.8	16	1981
0.7	14	1711
0.6	12	1447
0.5	10	1187
0.4	8	934
0.3	6	688
0.2	4	448
0.1	2	219
0	0	0

Fig. 7: Pixels counts in function of current and power for different kV settings

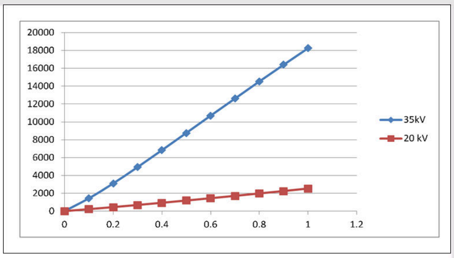

Fig. 8: Pixels counts in function of current for different kV set-tings

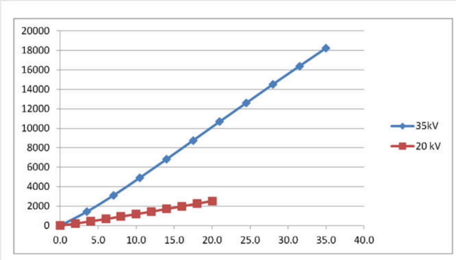

Fig. 9: Pixels counts in function of the power for different kV settings

Investigate the inverse square law

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- Move the detector to position SDD= 200.
- Take and save an image.
- Repeat this for SDD= 250, 300, 350, 400.
- Open the image viewer, correct for dark current and calculate the average pixel count in a relatively large area (see Fig. 6).
- Make a table and plot the results (see Fig. 10).

SDD	counts
200	25927
250	17700
300	12750
350	9188
400	7056

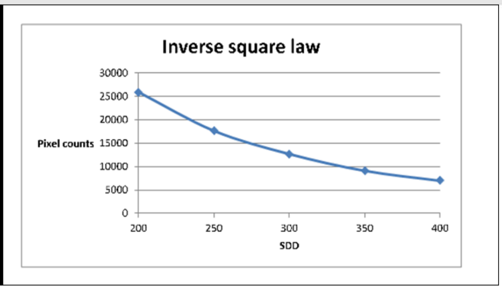

Fig. 10: Pixels counts in function of the SDD for same power and kV settings.

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